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A Study on Theoretical Calculation Method of Subway Safety Evacuation

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Abstract

Taking Hang Zhou Subway as research background, this article puts forward a new theoretical calculation suitable for subway safety evacuation, which is based on theoretical calculation of Japanese safety evacuation. The theoretical calculation can not only calculate total time necessary for safety evacuation, but also work out people's retention time on the way of different evacuation width clearly to specify the direction of improvement for subway fire-safety design. In addition, the evacuation simulation software named Pathfinder is used to simulate two evacuation situations when the train is stuck in tunnel when there is a fire. In comparison with the evacuation time and simulation result of two evacuation situations by theoretical calculation we can conclude a more accurate time necessary for safety evacuation to provide more reliable data for subway performance-based fire-protection design.

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Key words: subway fire, evacuation, theoretical calculation, numerical simulation, performance-based fire-protection.

Nomenclature

v	Evacuation speed(m/s)
L	Evacuation path length (m)
N	flow coefficient [per/ (m.s)]
B	Exit width (m)
Q	The number of evacuation (per)
N_{effc}	Effective flow coefficient [per/ (m.s)]
B_{effc}	Effective exit width (m)
H	Storey height (m)
n	Number of floors

1. Introduction

Metro is a personnel intensive place with the large flow of people. Once the fire breaks out, the metro entrance is less and the area is limited. In case of fire, lacking of oxygen often happens. Combustible matter generates a large amount of smoke. It's difficult to discharge smoke and abstract heat. And smoke move in the same direction with the evacuation of people [1]. Usually, smoke moves faster than people, so people aren't able to escape from the harm of smoke. Moreover, because a large amount of people get onto the station platform from the metro in a short time, the stampede and falling from a height cause a lot of casualties [2]. So it's essential to study further about the character of evacuation under the environment of metro fire.

At the present time, most of the study about safety evacuation focuses on the using software to imitate the time that

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safety evacuation needs under the different situations [3]. This method can just explain the safety of evacuation qualitatively. It does not show in detail what stage delays. Scholars such as Togawa [4] from Japan, Pauls [5] from Canada put forward the formula of evacuation. At the same time, Helbing [6] from Hungary, Yang Lizhong [7] from University of Science and Technology of China, Chen Baozhi [8] from Northeastern University and so on do a lot of work on evacuation. This article is based on the basic theory of the Japanese evacuation method [9,10]. It proposes the improved formula of evacuation time calculation. This method divides the evacuation area of different width into different evacuation stages, and it clearly display whether it is detained in the various stages and the time of retention. It is of great significance to the performance-based fire design in metro and fire security evacuation plan.

2. The theoretical calculation study of evacuation

2.1 Introduction of Japanese evacuation method

Japan has been used hand count method in the safety evacuation [10]. In 2000, Japan enacted the latest evacuation evaluation calculation method which has been written to the building standards method. The evacuation time of this method consists of three parts: calculation of room fire evacuation time, calculation of floor evacuation time, calculation of burning building evacuation time. And each part also consists of two parts, one is the evacuation start time, the second is evacuation time (including walking time and residence time). The table below shows the calculation of Japanese evacuation time.

Table 1. Calculation method of Japan evacuation time

The project and its meaning	Room on fire evacuation time calculation	Floor evacuation time calculation	the burning building evacuation time calculation
A-- area（㎡）	A—Fire room area （㎡）	A-- Fire floor area（㎡）	A-- Fire floor area（㎡）
ts-- Evacuation start time（min）	$t_s = \frac{\sqrt{A}}{30}$	$t_s = \frac{\sqrt{A}}{30} + 5(house)$ $t_s = \frac{\sqrt{A}}{30} + 3(others)$	$t_s = \frac{\sqrt{A}}{30} + 5(house)$ $t_s = \frac{\sqrt{A}}{30} + 3(others)$
travel--Walking time（min）	$t_{travel} = \frac{l_{\max}}{v}$	$t_{travel} = \frac{l_{\max}}{v}$	$t_{travel} = \frac{l_{\max}}{v}$
tq-- Residence time（min）	$t_q = \frac{\sum \rho A}{\sum N_f B_f}$	$t_q = \frac{\sum \rho A}{\sum N_f B_f}$	$t_q = \frac{\sum \rho A}{\sum N_f B_f}$

2.2 Calculation method of subway evacuation

Evacuation time refers to all the evacuees from the start of evacuation to the time when all the evacuees complete evacuation. Evacuation time generally divided into evacuation of fire area and evacuation of fire floor, its basic method consists of walking time and retention time [10].

1) Calculation for the first evacuation stage -------The carriage

The time required for walking is t_L (s):

$$t_L = L/v \tag{1}$$

Typical values about the walking speed can be reference in the table below.

Table 2. Forecast for evacuation of walking speed [11]

Personnel characteristics	Group action ability			
	The average walking speed (m / s)		flow coefficient (per / m)	
	level (V)	stairs (V)	level (N)	stairs (N′)
disabled person	0.8	0.4	1.3	1.1
People who are not familiar with the escape route	1.0	0.5	1.5	1.3
People who are familiar with the escape route	1.2	0.6	1.6	1.4

In addition, the evacuees Q gathered in front of the export which width is B, the time of all the stranded personnel through exports is t_B (S), as shown in formula

$$t_B = \frac{Q}{NB} \tag{2}$$

$$t_1 = t_L + t_B = L/v + Q/NB \tag{3}$$

2) Calculation for the second stage evacuation -- -- -- evacuation platform

Stranded situation decision: Σ NBi > $N_{effc}B_{effc}$, stranded will happen; Among them, N_{effc} is effective flow coefficient, B_{effc} is effective width. Without the stranded:

$$t_2 = L_{2i}/v \tag{4}$$

When there is stranded:

$$t_{1,2} = T_S + (\sum Q - Q_{出}) / N_{effc} B_{effc} \tag{5}$$

3) Calculation for the third stage evacuation -- -- -- the stairs

$$L_{平台} = \frac{\pi B_{effc}}{2} \approx 1.5 B_{effc} \tag{6}$$

$$t_3 = 4H(n-1) + \frac{(n-1)L_{平台}}{v} = (4H + 1.5B_{effc})(n-1) \tag{7}$$

4) Evacuation for the fourth stage -- -- -- connecting passage

$$t_4 = L_4/v \tag{8}$$

The total evaluation time:

$$t_{1-4} = t_{1-2} + t_3 + t_4 \tag{9}$$

2.3 The method of evacuation calculation on evacuation time prediction

1. The first kind of evacuation calculation results

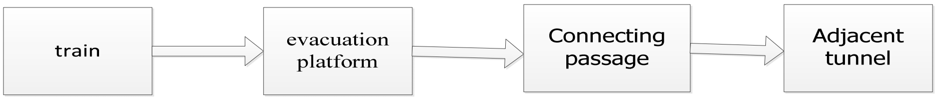

Fig. 1. Illustration of the first kind of evacuation

1) The selection of basic parameters

Train size is19.0x2.8x3.8, the rated load of the carriage with the driver's office set for 230, for the carriage has 245 staffs without the driver chamber, car door is 1.3 meters wide, effective evacuation platform width is 0.8 meters and 600 meters long, contact about 7 meters long, effective evacuation is 1 m wide.

2) The calculation procedure of evacuation time

(1) Calculation for the first stage evacuation -------The carriage

The time required for walking is t_L (s):

$$t_L = L/v = 19/1 = 19(s) \tag{10}$$

(2) Calculation for the second stage evacuation -- -- -- evacuation platform

Stranded situation decision: $\sum$ NBi > $N_{effc}B_{effc}$, stranded will happen; Among them, N_{effc} is effective flow coefficient, B_{effc} is effective width. Train is illustrated below:

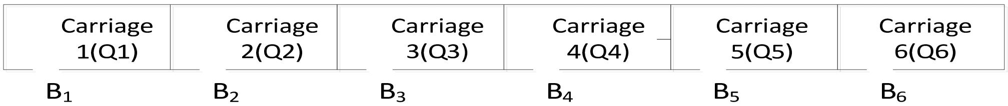

Fig. 2. Illustration of the carriage

Because evacuation platform is 600 m, the measured distance from each carriage to evacuation platform end is L1 = 602, L2 = 621, L3 = 640, L4 = 659, L5 = 678, L6 = 697

The first carriage:

$$NB_1 = 1.5\times1.3 \le N_{effc}B_{effc} = 1.3\times1.5 \tag{11}$$

Just can pass, stranded didn't happen;

The second carriage:

$$N(B_1 + B_2) = 1.5\times(1.3+1.3) \ge N_{effc}B_{effc} = 1.3\times1.5 \tag{12}$$

Stranded happen, namely the second stream of people stranded, Calculation is as follows:

$$t_{s1} = L_1/v = 602/1 = 602, \quad t_{s2} = L_2/v = 621/1 = 621, \quad t_{s3} = L_3/v = 640/1 = 640$$

$$t_{s4} = L_4/v = 659/1 = 659, \quad t_{s5} = L_5/v = 678/1 = 678, \quad t_{s6} = L_6/v = 697/1 = 697$$

The order of the evacuation: $Q_1 \longrightarrow Q_2 \longrightarrow Q_3 \longrightarrow Q_4 \longrightarrow Q_5 \longrightarrow Q_6$

By the second stream of people stranded concluded:

$$T_s = t_{s2} = 621 \quad , \quad Q_{出} = M_1 = NB_1(T_s - t_{s1}) = 1.5\times1.3\times17 \approx 37(per)$$

$$t_{1,2} = T_S + {(\sum Q - Q_{出})}\Big/{N_{effc} B_{effc}} = 621 + \frac{1455 - 37}{1.3\times0.8} = 1985\ (s)$$

(3) Calculation for the third stage evacuation -- -- -- connecting passage

Stranded situation decision: Σ NBi > $N_{effc}B_{effc}$, stranded will happen; Among them, N_{effc} for effective flow coefficient, B_{effc} for effective width. From the evacuation platform into the connecting passage B_i is 0.8 m, B_{effc} is 1 m.

$$NB_i = 1.5\times0.8 \le N_{effc} B_{effc} = 1.3\times1$$

Just can pass, stranded didn't happen;

$$t_3 = {L_t}\big/{v} = 7\big/1 = 7(s)$$

The total evacuation time:

$$t_{总} = t_L + t_{1,2} + t_s = 19 + 1985 + 7 \approx 2012(s)$$

2. The second kind of evacuation calculation results

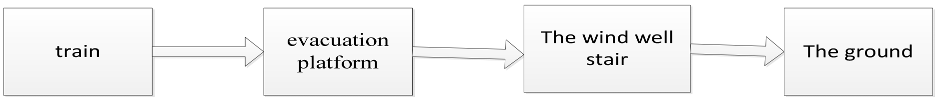

Fig. 3. Illustration of the second kind of evacuation

1) The selection of basic parameters

Train size is19.0x2.8x3.8, the rated load of the carriage with the driver's office set for 230, for the carriage has 245 staffs without the driver chamber, car door is 1.3 meters wide, effective evacuation platform width is 0.8 meters and 600 meters long, Wind well stair is 3 layers, each layer of 3 meters, 1.1 meters wide stairs.

2) The evacuation from trains to evacuate platform with the first evacuation situation is the same, so the first two evacuation time for evacuation stage

$$t_L = L\big/v = 19\big/1 = 19(s)$$

$$t_{1,2} = T_S + {(\sum Q - Q_{出})}\Big/{N_{effc} B_{effc}} = 621 + \frac{1455 - 37}{1.3\times0.8} = 1985(s)$$

3) Calculation for the third stage evacuation -- -- -- the wind well the stairs

Stranded situation decision: Σ NBi > $N_{effc}B_{effc}$, stranded will happen; Among them, N_{effc} is effective flow coefficient, B_{effc} is effective width. From the evacuation platform into the connecting passage B_i is 0.8 m, B_{effc} is 1 m.

$$NB_i = 1.5\times0.8 \le N_{effc} B_{effc} = 1.3\times1.1$$

Just can pass, stranded didn't happen;

$$t_3 = 4H(n-1) + \frac{(n-1)L_{平台}}{v} = (4H + 1.5B_{effc})(n-1) = (4\times3 + 1.5\times1.1)(3-1) = 27.3(s)$$

The total evacuation time:

$$t_{总} = t_L + t_{1,2} + t_s = 19 + 1985 + 27.3 \approx 2032(s)$$

3. Numerical simulation research

Under the subway fire evacuation, use the evacuation software Pathfinder to simulate the evacuation. Two types are considered in the simulation of different personnel, personnel proportion and evacuation speed [12]. The following content shows the evacuation route of evacuation time.

3.1 Analysis to the first evacuation simulation results

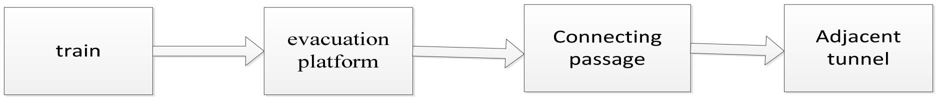

Fig. 4. Illustration of the first kind of evacuation

As shown in the above, the first evacuation situation is shown that evacuees evacuate from evacuation platform to connecting passage, then to adjacent tunnel. The selection of basic parameters affecting the evacuation time are shown as follows:

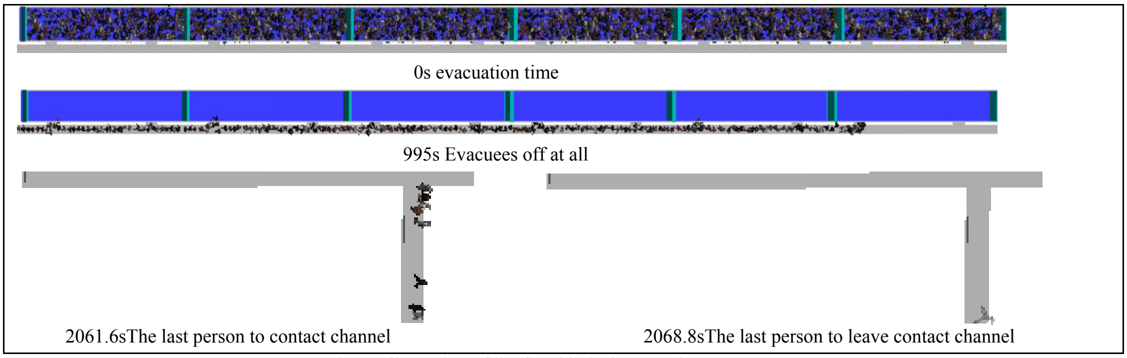

Fig. 5. Illustration of the first kind of evacuation

Train size is19.0x2.8x3.8, the rated load of the carriage with the driver's office set for 230, for the carriage has 245 staffs without the driver chamber, car door is 1.3 meters wide, effective evacuation platform width is 0.8 meters and 600 meters long, contact about 7 meters long, effective evacuation is 1 m wide.

3.2 The second evacuation simulation results analysis

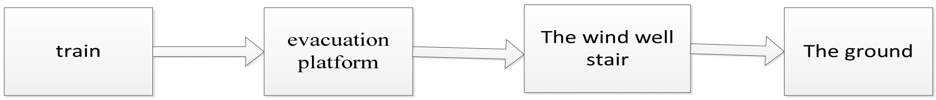

Fig. 6. Illustration of the second kind of evacuation

As shown in the above, the second evacuation situation is shown that evacuees evacuate from evacuation platform to the wind well stair, then to the ground. The selection of basic parameters affecting the evacuation time are shown as follows:

Train size is19.0x2.8x3.8, the rated load of the carriage with the driver's office set for 230, for the carriage has 245 staffs without the driver chamber, car door is 1.3 meters wide, effective evacuation platform width is 0.8 meters and 600 meters long, Wind well stair is 3 layers, each layer of 3 meters, 1.1 meters wide stairs.

4. Comparison and analysis

The comparison of the total evacuation time which comes through the theoretical calculation compared with the numerical simulation is as follows.

Table 3. Comparison of evacuation time table

	Theoretical calculation of evacuation time（s）	Simulation evacuation time(s)
The first situation of evacuation	2012	2069
The second situation of evacuation	2032	2086

It can be seen from the table that the length of simulated calculation time is from 50s to about 60s more than theoretical calculation time's. The main reason here is that the evacuees were divided into four categories in simulated calculation. They are the elderly, young man, young woman and child. The Simulated walking speed and proportion of persons are described in the following table.

Table 4. The revised different types of evacuation speed [12]

Personnel type	speed（m/s）	Personnel proportion	First car/stern	The middle carriage
Old man	0.75±0.10	3.0%	7	7
Adult men	1.30±0.10	52.0%	97	102
Adult women	1.10±0.10	42.0%	119	128
child	0.90±0.10	3.0%	7	8

However, we can't simultaneously take into account the different evacuation speed of different types of people in the theoretical calculations. Therefore, the average walking speed adopted is 1m/s in this theoretical calculation. Hence, the differences of evacuation time brought about due to the speed selected by the different ways are within the allowable range of the error.

5. Conclusions

For the occupants' evacuation under the circumstance of Hangzhou subway fire, we summarize a set of theoretical equations suitable for the subway stuff on the basis of Japan evacuation method. In comparison with the software simulation, the theoretical calculation obtained conclusions as follows:

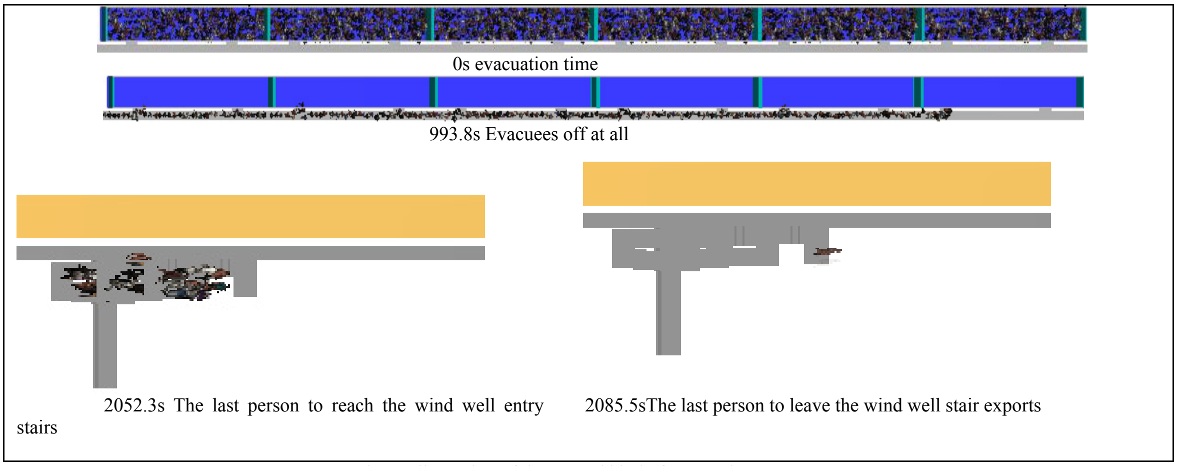

Fig. 7. Illustration of the second kind of evacuation

(1) Comparing the calculation results of two methods above, we can find that the evacuation time has little difference between theoretical calculation and pathfinder. As both are summarized and extended on the basis of massive statistical data, the two methods have certain credibility over the prediction of evacuation time, although both have made certain assumptions in calculation and have their own rationales.

(2)As you can see from the theoretical calculation, the evacuation time of each zone is different. What's more, the residence time of subway stuff from carriage to evacuation platform accounts for a large proportion of the whole evacuation time. Properly broadening the evacuation platform would improve the evacuation efficiency. This provides direction of improvement for the performance-based assessment of subway fire.

(3)Through the comparisons of several kinds of evacuation situation, we can find that the most effective way is to pass from evacuation platform to connecting passage and air shaft, then go out of harm's way. This illustrates the possibility of evacuation through connecting passage and air shaft under the circumstance of subway fire.

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